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The effect of helical pitch on the behaviour of helically confined HSC beams

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ABSTRACT

The strength and ductility of HSC beams are enhanced through the application of helical reinforcement located in the compression region of the beams. The pitch of helix is an important parameter controlling the level of strength and ductility enhancement of over reinforced high strength concrete beams. This paper presents an experimental investigation of the effect of helix pitch on the beam behaviour through testing five helically confined full scale beams. The helix pitches were 25, 50, 75, 100 and 160 mm. Beams' cross section was 200×300 mm, and with a length of 4 m and a clear span 3.6 m subjected to four point loading, with emphasis placed on the midspan deflection. The main results indicate that the helical effectiveness is negligible when the helical pitch is 160 mm (helix diameter), the concrete cover spalling off load increases linearly as the helical pitch increased, and the ultimate load decreases as the helical pitch increases. Finally, there is a considerable release of strain energy responsible for spalling off the concrete cover.

Keywords: ductility; high strength concrete; reinforced concrete; helical reinforcement.

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1. INTRODUCTION

The development of the construction industry has led to the continual improvement of construction materials where high strength concrete of 100 MPa compressive strength and reinforcement of 500 MPa yield strength are used in beams and other construction members. Higher strength of materials is usually associated with a decrease in the ductility of the materials compared to their lower strength counterparts. Helical reinforcement can be used to achieve the required ductility. It is generally accepted that helical confinement is more effective than the rectangular ties in increasing the strength and ductility of confined concrete. Helical reinforcement is effective for concrete under compression to increase the ductility as well as the compressive strength by resisting lateral expansion due to Poisson's effect upon loading. Herein the helical reinforcement is used in the compression zone of the beams. The effectiveness of helical confinement depends on different important variables such as helical pitch and its diameter.

This paper presents the experimental results of testing five full-scale beams with 4000 mm length and a cross section of 200 mm in width and 300 mm in depth. All variables such as concrete compressive strength and longitudinal reinforcement ratio are kept the same except the helical pitch. The helix pitch was 25, 50, 75, 100 and 160 mm.

2. EXPERIMENTAL PROGRAM

Sheikh and Uzumeri [1] examined the effect of different variables on the behaviour of the strength and ductility of columns by testing 24 specimens. The results pointed out to the significant influence of the helical pitch on the behaviour of confined concrete. Shin et al. [2] tested 36 beams, four of which to study the effect of tie spacing on ductility. The results did not show clearly the importance of confinement spacing. It may be because the spacing studied was only 75 and 150 mm which did not provide adequate data to figure out the importance of confinement spacing. Hadi and Schmidt [3] tested seven high strength concrete (HSC) beams helically confined in the compression zone, all beams had the same helical pitch of 25 mm to study different variables excluding the helical pitch. However, the literature indicates the importance of helical pitch, but there is no quantitative data for over reinforced helically confined HSC beams.

The aim of the experimental program in this study is to investigate the behaviour of over-reinforced HSC helically confined beams and determine the effect of helical pitch on their strength and ductility. Helical pitch was the only parameter selected for investigation in the current experimental program. In the test program reported herein, a total of five beams with five different pitches 25, 50, 75, 100 and 160 mm were tested. All five beams had the same dimensions; generic details of the beams are shown in Figure 1. Each of the beams was reinforced with 4N32 bars (32 mm deformed bars of

500 MPa tensile strength and of normal ductility). Stirrups of plain 10 mm diameter (250 MPa tensile strength) were provided at either third end of the beams at a spacing of 80 mm. Two 10 mm plain bars were installed at the top of the beams at either third in order to keep the ties in-place. The helix was made of 8 mm plain bars with 500 MPa tensile strength. All beams were cast on the same day using five wooden moulds. The beams were then cured by covering with wet Hessian bags.

The alphanumeric characters in the titles of the beams (e.g. 8HP25) have the following meaning. The first number presents the diameter of helical steel. The two letters after the first number indicates the only variable is helical pitch. The second number refers to the helical pitch in mm.

2.1 Materials

The helical reinforcement was 8 mm plain bar with 500 MPa tensile strength. Each beam had four longitudinal deformed steel bars, 32 mm diameter and 500 MPa tensile strength. Figures 2 and 3 show the stress-strain curves of the tensile strength tests of the helical and the longitudinal reinforcement. The concrete used in this experimental program was supplied as a ready mix by a local supplier and was specified to have a 10 mm maximum aggregate size, also super plasticiser was added to the concrete in order to obtain the considered necessary workability to gain 100 MPa, however the average compressive strength of concrete gained was 80 MPa after 40 days when the beams were tested.

2.2 Instrumentation

All beams were heavily instrumented. Reinforcement steel deformation was measured using electrical – resistance strain gauges (20 mm length) glued to the steel bars at mid-span of the bar and 300 mm away from the mid-span on both sides of the bar. Also the strains of the helical reinforcement were measured using electrical – resistance strain gauges (5 mm) glued at the bottom, top and sides of the helical reinforcement at the mid-span of the beam and 300 mm away from the mid-span of the beam. The strain on the compression zone of the beam was measured using two electrical – resistance strain gauges (60 mm length) glued on the top surface at mid-span of the beam.

It was difficult to complete recording the strains at the top of the compression zone because of the spalling off the cover. As such, two embedment gauges were used one at a depth of 40 mm at the beam's mid-span and the other one at a depth of 20 mm at 300 away from the mid-span of the beam.

The beams were tested under four-point loading regime in the strong floor of the civil engineering laboratory at the University of Wollongong. The displacement-controlled load was applied using 600 kN actuators. The mid span deflection of the beam was measured using linear variable differential transformers (LVDTs). All the data were recorded using Smart System installed in a PC computer.

3. ANALYSIS OF TEST RESULTS

The behaviour of the helically confined beams is different from unconfined beams because of the spalling off phenomenon. It is noted that the load increases as the deflection and strains increase until the spalling off phenomenon occurred and then the load drops while the strain increases, because of the helical confinement effect. However, the load increased again as the deflection increased until the point where the load decreases gradually as the deflection increases. It is noted that the maximum load recorded for beam 8HP25 was 346 kN which is greater than the concrete cover spalling off load but for the other beams the maximum load recorded was the concrete cover spalling off. Figures 4 and 5 show the two general behaviours (load- mid span deflection) of the HSC beams helically confined used in this study based on the experimental results.

A summary of the test results is presented in Tables 1 and 2. The observed load versus strain and load versus mid-span deflection are presented and discussed in the following two sections.

3.1 Load versus strains

The strain at top surface of the beam (concrete cover) was recorded until the concrete cover spalling off occurred (Table 2). The interesting point is there was no significant difference between concrete cover spalling off strain (top surface). However, the average concrete cover spalling off strain for the five beams was 0.0033, which is in agreement with ACI 318R-02 [4] and AS3600 [5]. Figures 6-10 show the load versus strain at a depth 40 mm. The significant differences are between the failure strains, where the failure strain for Beam 8HP25 was 1.4, 2.6 and 6.8 times of the failure strain of Beams 8HP50, 8HP75 and 8HP160, respectively. It is to be noted that the failure strain of Beam 8HP100 was not recorded, because of the premature damage of the embedment gauges before the failure load.

Figure 11 shows the relation between the concrete spalling off load versus helix pitch. It is worth noting that the spalling off load increased linearly as the helical pitch increased. The result of the Beam 8HP75 may be excluded due to a possible experimental error. Based on this finding it can be concluded that the spalling off load is directly proportional to the helical pitch.

It is a common believe that the closely spaced reinforcement physically separates the concrete cover from the core, causing the early failure of the cover. This statement does not consider the effect of helical diameter or the other variables such as helical yield strength, concrete compressive strength and longitudinal reinforcement ratio, which may have significant effect. It is believed that cover spalling off occurs when the strain in between confined and unconfined concrete changes significantly. In other words, when the strain at the cover becomes less than the strain of the confined concrete, which does not follow the strain gradient. The experimental results presented in Figures 6-10 and summarised in Table 2 prove that the sudden change in strain (energy release) causes spalling off the concrete cover. For example in Beam 12HP25 the strain at 40 mm depth from the top surface just before spalling off the concrete cover was 0.001386 and just after spalling off the concrete cover was 0.002716 (measured at 40 mm depth), in other words the strain just after spalling off the concrete cover had a value of twice the strain just before spalling off the concrete cover. Then the top surface strain just after the cover spalling off could be estimated to be twice the top surface concrete strain after spalling off (i.e.$2\times0.00324= 0.00648$). This remarkable change in strain causes the spalling off the concrete cover. The Beam 8HP160 had no sudden change in strain (strain energy release) because of the negligible effect of the confinement, where the maximum strain was 0.0035 (no spalling off phenomenon).

3.2 Load- mid span deflection of tested beams

From Figure 12 it could be noted the remarkable effect of helical pitch on displacement ductility. Beams, which have helical pitches of 25, 50, 75 and 100 mm failed in a ductile manner. The level of the ductility depends on the helical pitch. The Beam 8HP160 failed in a brittle mode, as the upper concrete in the compression zone was crushed and the maximum load was 376 kN and then dropped to 94 kN. This drop indicates the effect of confinement is negligible when the pitch is equal to the confinement diameter, which is in agreement with the experimental results by Iyengar et al. [6] and Martinez et al. [7]. Figure 13 shows the relation between the helical pitch and ultimate mid-span deflection. Beam 8HP25 had a maximum deflection of 185 mm. The mid-span deflection of the beams are reduced as the pitch increases.

Deflection ductility index is defined as the ratio of ultimate deflection to the yield deflection. Figure 14 shows that the deflection ductility index increases as the helical pitch decreases. The yield deflection for Beams 8HP25, 8HP50, 8HP75, 8HP100 and 8HP160 were 29, 31, 40, 34 and 39 mm, respectively, and the ultimate corresponding deflections were 185, 68, 45, 41 and 39, respectively. It should be noted that, there is no significant difference between the yield deflections for the five beams compared to the ultimate deflections where a considerable difference is clear. Hence, it can be concluded that the deflection ductility index is affected significantly by the ultimate deflection. It could also be concluded that the helical pitch has a significant effect on the ultimate deflection but less significant effect on the yield deflection. Figure 15 shows the ultimate deflection of Beams 8HP25, 8HP50, 8HP75 and 8HP100 and Figure 16 shows concrete core of Beam 8HP25. It is noted that the 10 mm diameter steel bar, which was used to fix the helix pitch during casting the concrete has buckled only in the beams that have high helix pitch 8HP75 and 8HP100. Figure 17 shows the steel bar used for keeping the helix pitch fixed has buckled for Beam 8HP100. However, this buckling most probably occurred after cover spalling off, because the concrete cover spalling off load for Beams 8HP75 and 8HP100 was greater than the concrete cover spalling off load for Beams 8HP25 and 8HP50. The helix diameter was small (8 mm) which could not resist the stress produced due expansion of the concrete core, that led to helix fracture. It is noted that the helix of Beams 8HP25, 8HP50, and 8HP75 had helix fracture. Figure 18 shows the helix fracture for Beam 8HP75.

Helical pitch is an important parameter in enhancing the strength and ductility of beams. However, building codes such as ACI 318R-02 [4] and AS3600 [5] do not take helical pitch or tie spacing as an explicit design parameter. For Example, equation 1 of ACI 318R-02 [4] for the design of helical reinforcement of columns does not include the helical pitch directly. The design is only for the quantity of lateral steel (volumetric ratio) without specifying the pitch.

$$\rho_h = 0.45\left(\frac{A_g}{A_c} - 1\right)\frac{f'_c}{f_{yh}} \qquad (1)$$

where ρ_h is the total volumetric ratio of helices; A_g is the gross area of the section; A_c is the area of the core; f_c' is the concrete compressive strength and f_{yh} is the yield stress of helical reinforcement.

Equation 1 was derived to compensate the strength lost by the spalling off the concrete cover. There is a need for an equation to compensate the strength as well as the ductility taking the helical pitch into consideration.

3.3 Comparison between helix and tie confinement

It is well known that the confinement by helix is generally much more effective than that by rectangular or square ties. Hatanaka and Tanigawa [8] stated that the lateral pressure produced by a rectangular tie is about 30 to 50 percent of the pressure introduced by a helix. That will be the case for compression concrete in columns or beams. However, helix confines the concrete more effectively than rectangular ties because helix applies a uniform radial stress to the concrete along the concrete member, whereas a rectangular tie tends to confine the concrete mainly at the corners. Also the effective area between the ties is reduced, as shown in Figure 19, thus using helical confinement in the compression zone of rectangular beams is more effective than rectangular ties even though there is a very small portion of compression concrete that is not confined. This area is at the corner as shown in Figure 20. However to prove experimentally that the helix is more effective than the rectangular ties, there is a need to compare beams helically confined with beams confined using rectangular ties.

The comparison between the effect of helix with rectangular confinement of over reinforced concrete beams using the experimental data of Mansur et al. [9] and Ziara et al. [10] was very difficult because of different variables such as size and span of the beam, tie spacing and longitudinal reinforcement ratio. The comparison between the effectiveness of helix and tie in the compression zone of HSC beams will be undertaken during the next stage of the extensive experimental program at the University of Wollongong.

The results of the tests in this study correlate very well with other tests done and reported, for example [3, 11-13].

More tests are to be done on larger specimens to investigate the behaviour of such beams when helically confined in the compression zone.

4. CONCLUSIONS

The experimental program in this study is to investigate and provide experimental evidence about the significant effect of helical pitch on the behaviour of HSC beam. Five over reinforced HSC beams helically confined were tested. Conclusions can be drawn about the behaviour of these beams with different helical pitch of 25, 50, 75, 100 and 160 mm.

The behaviour of the beam with helical pitch of 160 mm (equal to the core diameter of the beam) has shown to be very brittle in its failure, providing no plateau region in its load mid-span deflection curve. The concrete spalled off at failure load. The conclusion drawn from testing the beams is that the confinement effect is negligible when the helical pitch is equal to or greater than the core diameter for helically confined beams.

The behaviour of the other beams with helical pitch of 25, 50, 75 and 100 mm has shown to be ductile and the level of ductility is based on the helical pitch. The helixes effectively confined the compressive region when the helical pitch was reduced. It is interesting to note that spalling off load increases as the helical pitch increases. In other words, spalling off load is directly proportional with the helical pitch.

The common reason for the spalling off phenomena is that closely pitched helixes physically separate the concrete cover from the core. However, the experimental results show that the cover spalling off occurred when the strain in between confined and unconfined concrete changed significantly. This change is affected by helical pitch as well as other parameters such as helical diameter and tensile strength. In other words, there is a considerable release of strain energy responsible for spalling off the concrete cover. The quantity of strain energy release is affected by different factors, one of which is helical pitch. Finally, this study has shown that adopting a suitable helix pitch can enhance both the strength and ductility of HSC beams reinforced with high strength steel.

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Table 1 - Summary of beam results

Beam specimen	Load just before cover spalling off, kN	Load just after cover spalling off, kN	Failure load,kN	Yield deflection Δ_y, mm	Ultimate deflection Δ_u, mm	Displacement ductility index Δ_u / Δ_y
8HP25	297	229	346	32	185	5.7
8HP50	324	306	310	31	68	2.2
8HP75	381	260	300	40	45	1.1
8HP100	326	260	250	34	41	1.2
8HP160	376	*94	94	39	39	1

* the load dropped suddenly from 376 to 94 kN

Table 2- Summary of beam strains

Beam specimen	Measured top surface strain just before spalling off concrete cover	Measured strain at 40 mm depth just before spalling off concrete	Measured strain at 40 mm depth just after spalling off concrete	Measured strain at 40 mm depth at failure load
8HP25	0.0034	0.001386	0.002716	0.012459
8HP50	*	0.001273	0.00163	0.009155
8HP75	0.0034	0.002077	0.0049	0.004867
8HP100	0.003	0.00119	0.00157	*
8HP160	0.0035	0.001824	0.001824	0.001824

* not available

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Figure 18. Helix bar fracture of Beam 8HP75

Figure 19. Effective confined concrete for helix and rectangular tie

Figure 20. Confined and unconfined compression concrete in beams

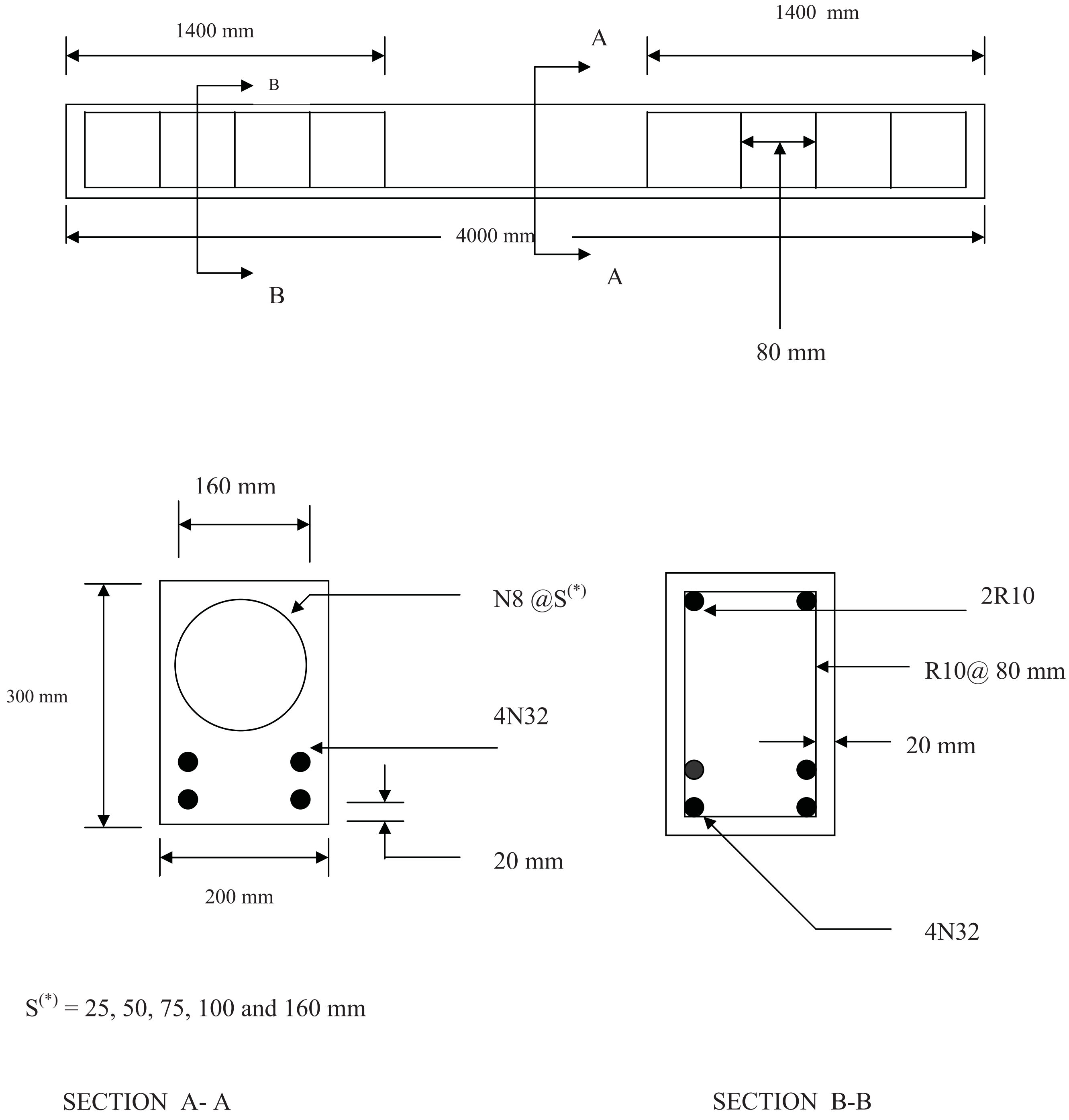


Figure 1. Loading configuration and specimen details.

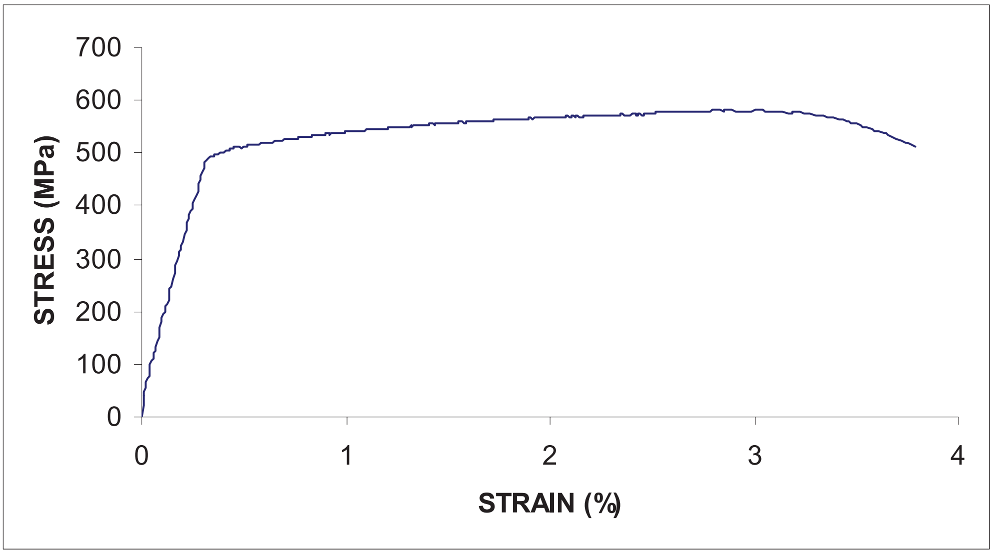


Figure 2. Tensile stress strain curve for the helical steel with 8 mm diameter

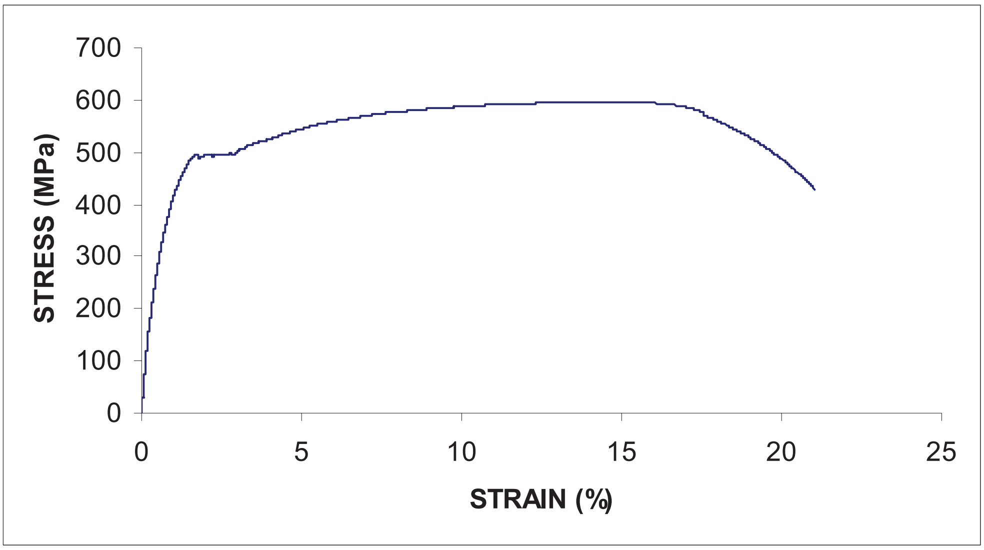


Figure 3. Tensile stress- strain curve for the longitudinal steel with 32 mm diameter

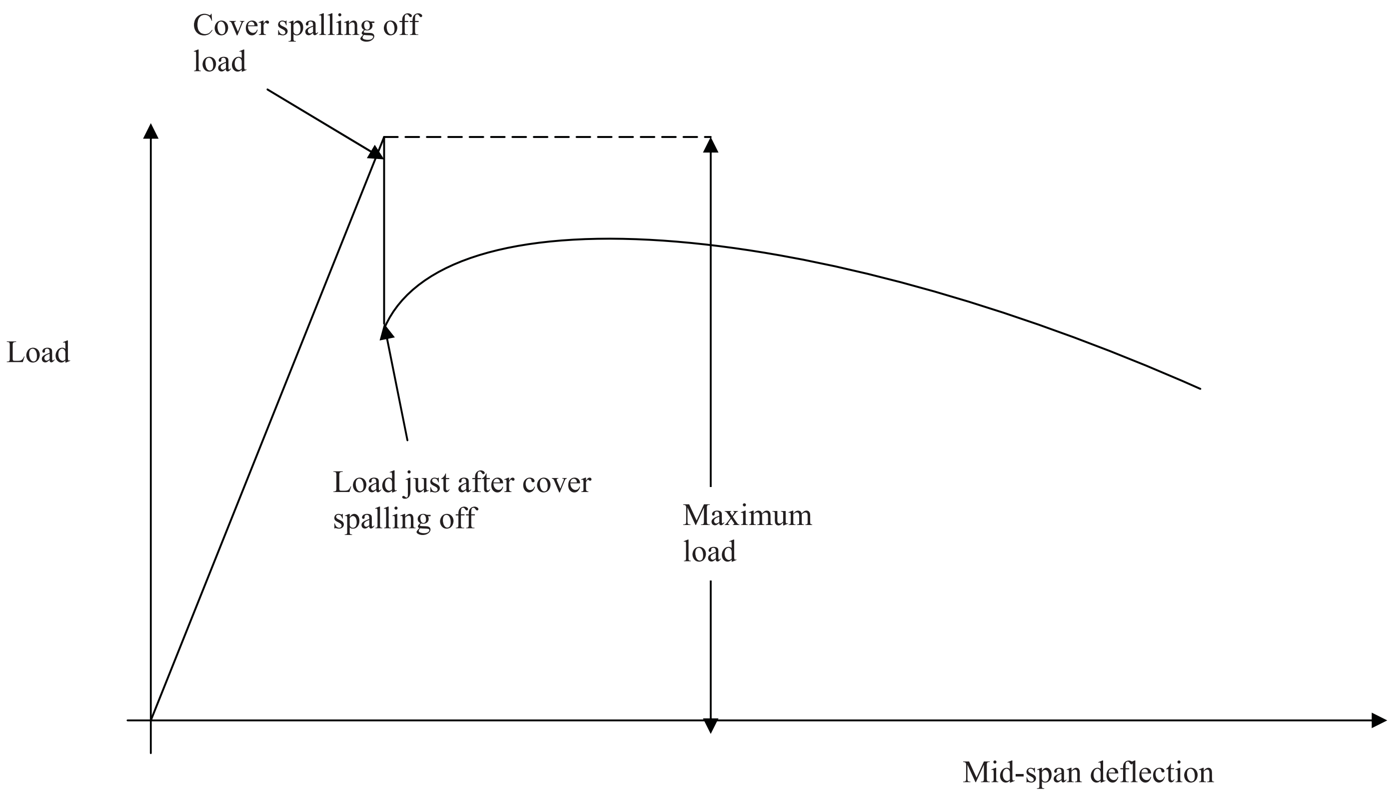


Figure 4. General behaviour of load- mid span deflection of Beams 8HP50, 8HP75 and 8HP100

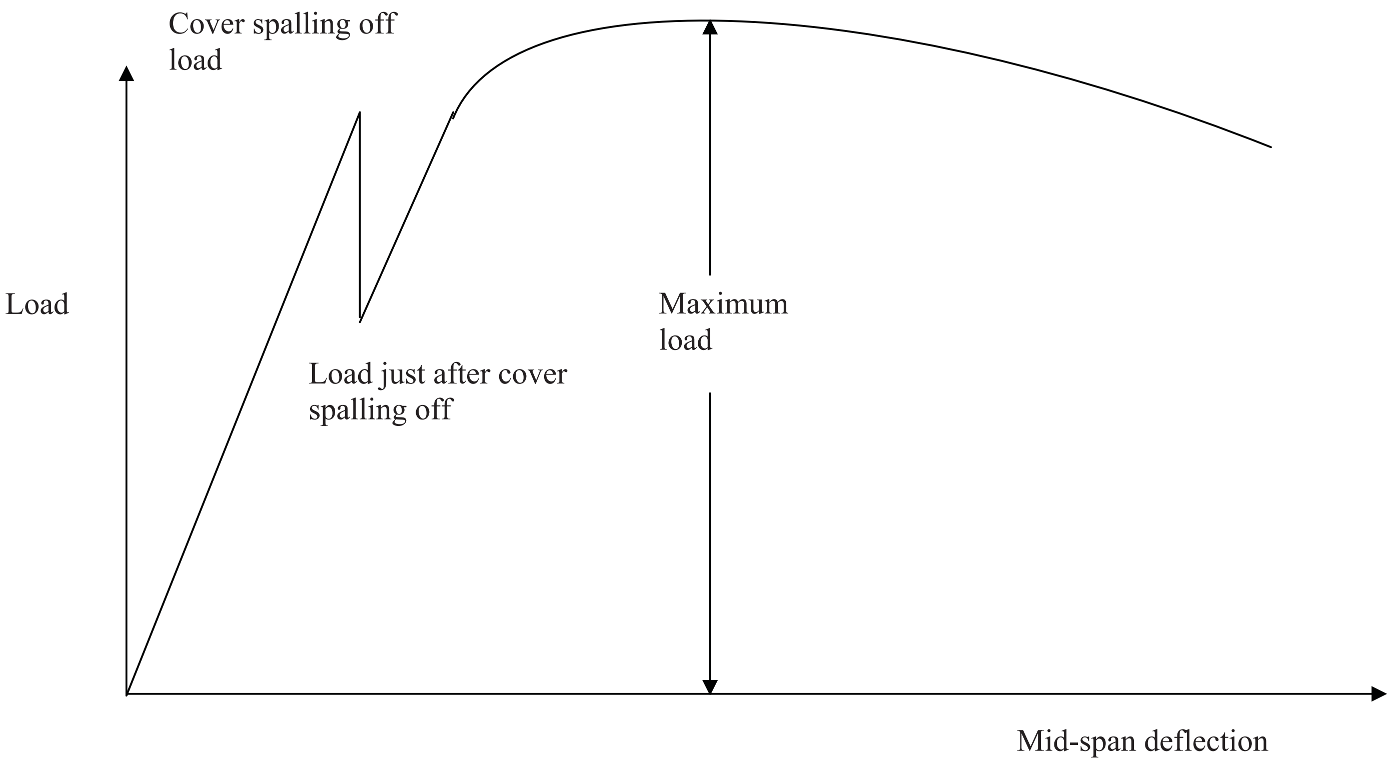


Figure 5. General behaviour of load- mid span deflection of Beams 8HP25

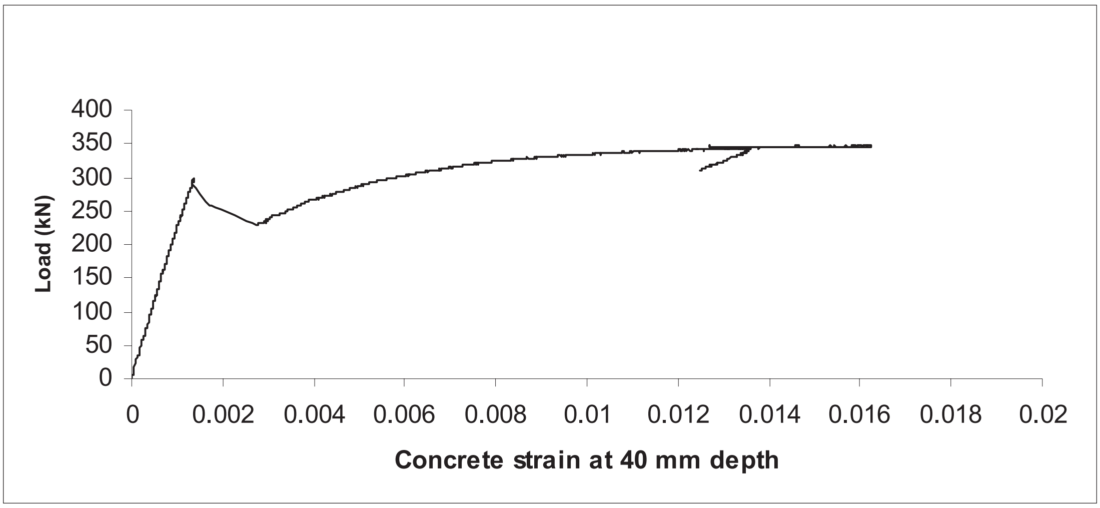


Figure 6. Load versus concrete compressive strain at 40 mm depth from top surface for Beam 8HP25.

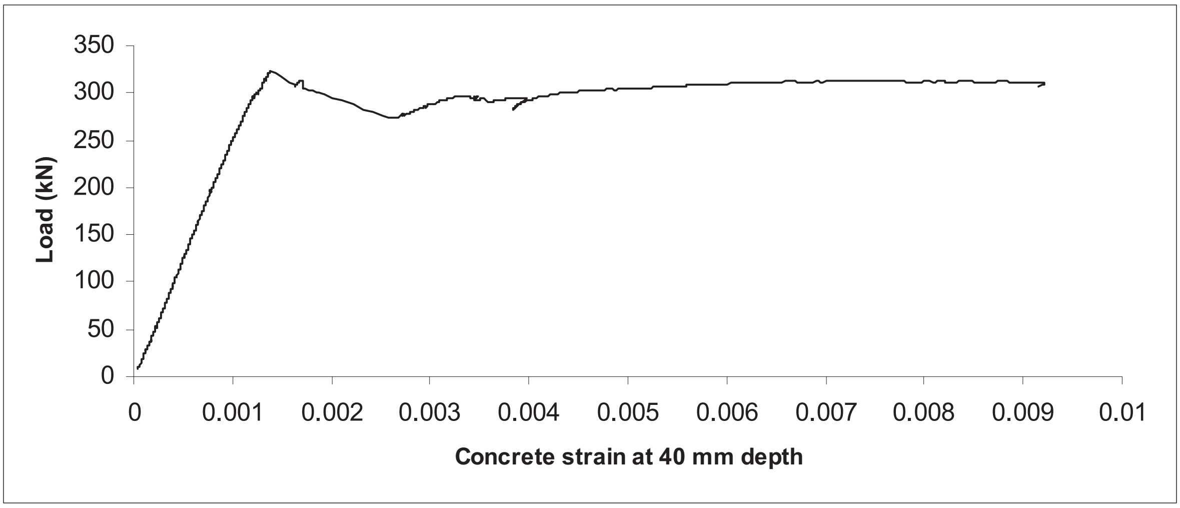


Figure 7. Load versus concrete compressive strain at 40 mm depth from top surface for the Beam 8HP50.

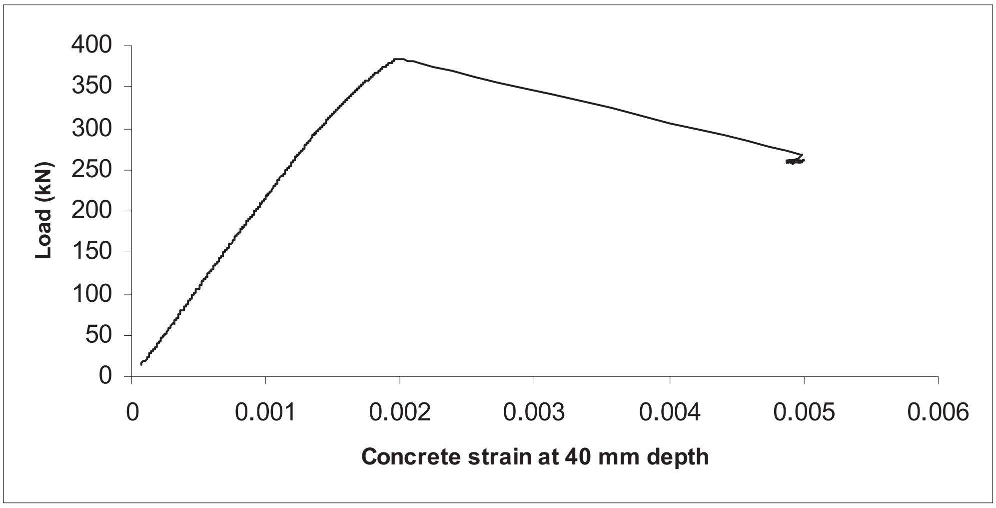


Figure 8. Load versus concrete compressive strain at 40 mm depth from top surface for the Beam 8HP75.

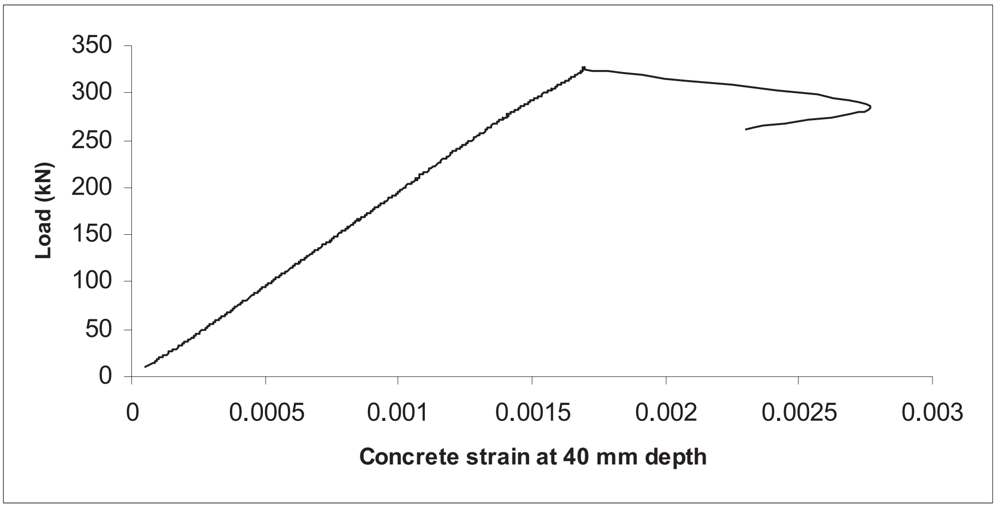


Figure 9. Load versus concrete compressive strain at 40 mm depth from top surface for the Beam 8HP100.

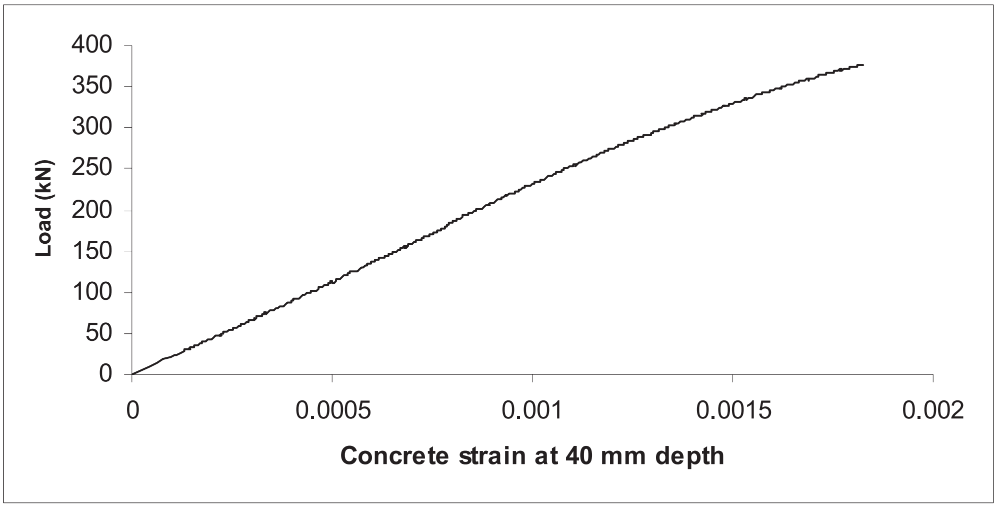


Figure 10. Load versus concrete compressive strain at 40 mm depth from top surface for the Beam 8HP160.

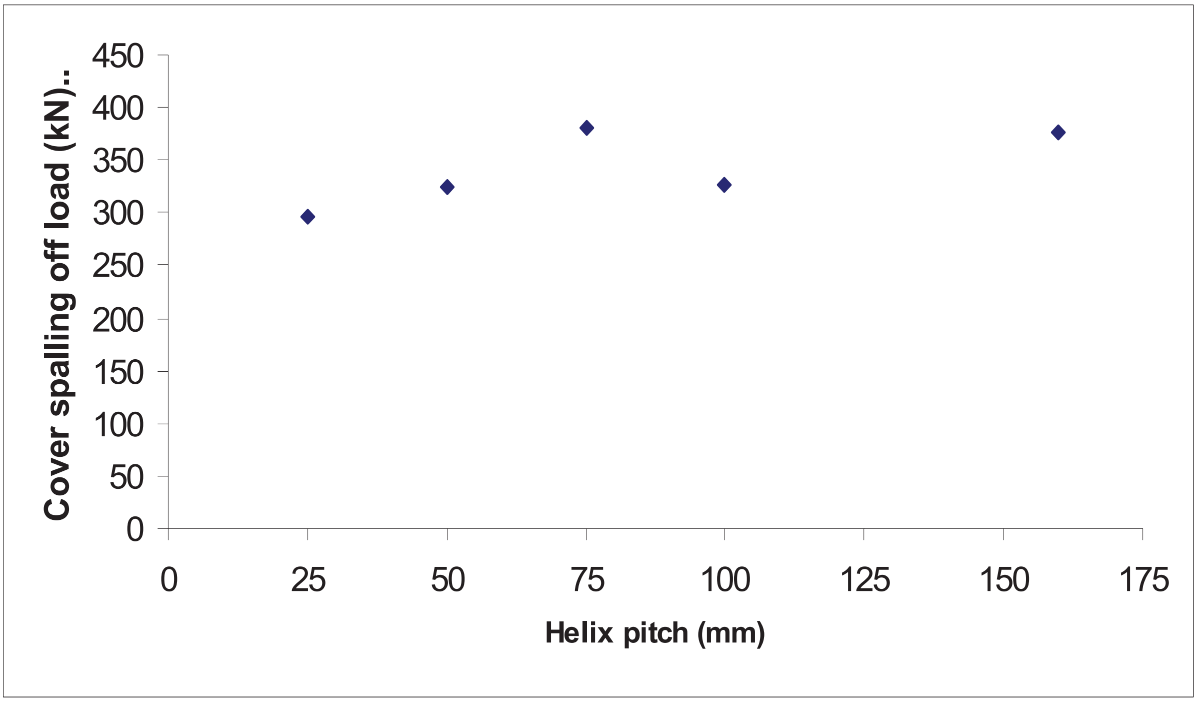


Figure 11. Cover spalling off load versus helix pitch

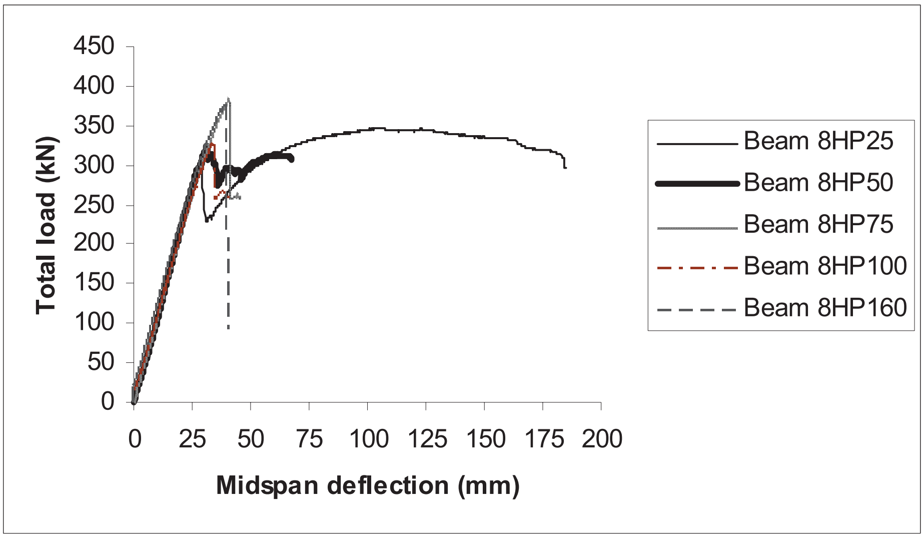


Figure12. Load-deflection curves for beams with different helix pitch

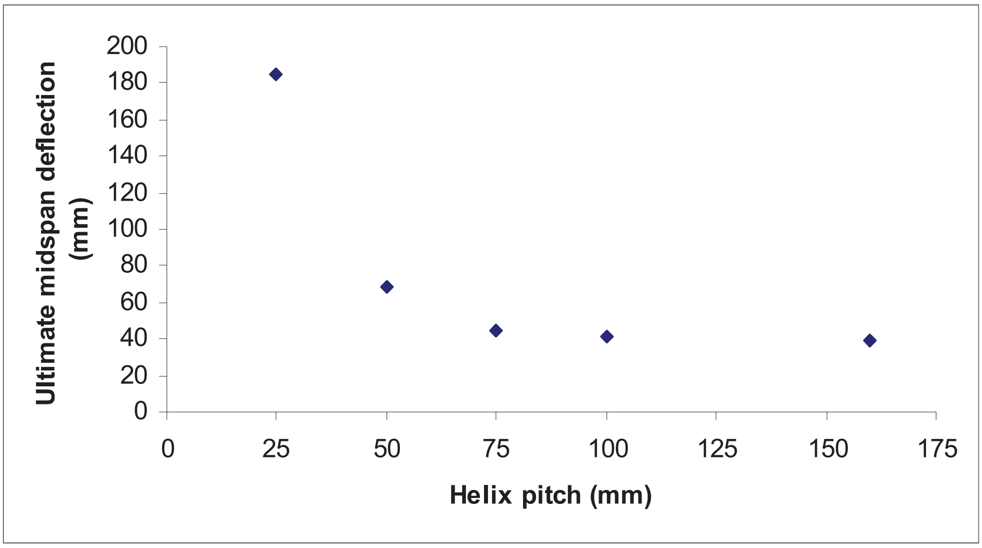


Figure 13. Ultimate deflection versus helix pitch

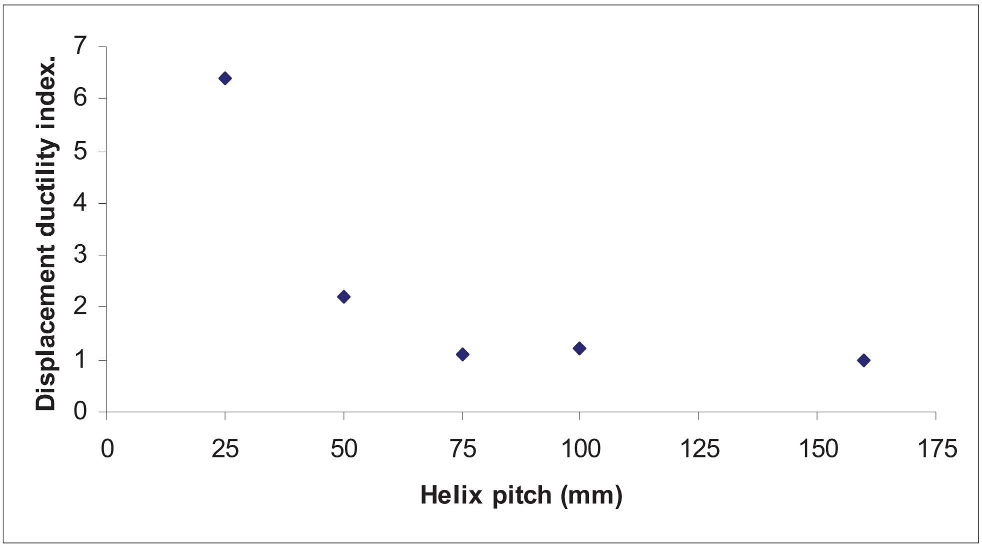


Figure 14. Effect of helix pitch on displacement ductility

Final deflection of Beam 8HP25

Final deflection of Beam 8HP50

Final deflection of Beam 8HP100

Final deflection of Beam 8HP75

Figure 15. Final deflection for beams helically confined with different helix pitch 25, 50, 75 and 100 mm

Figure 16. Core concrete of Beam 8HP25

Figure 17. Buckling in the steel bar of Beam 8HP100

Figure 18. Helix bar fracture of Beam 8HP75

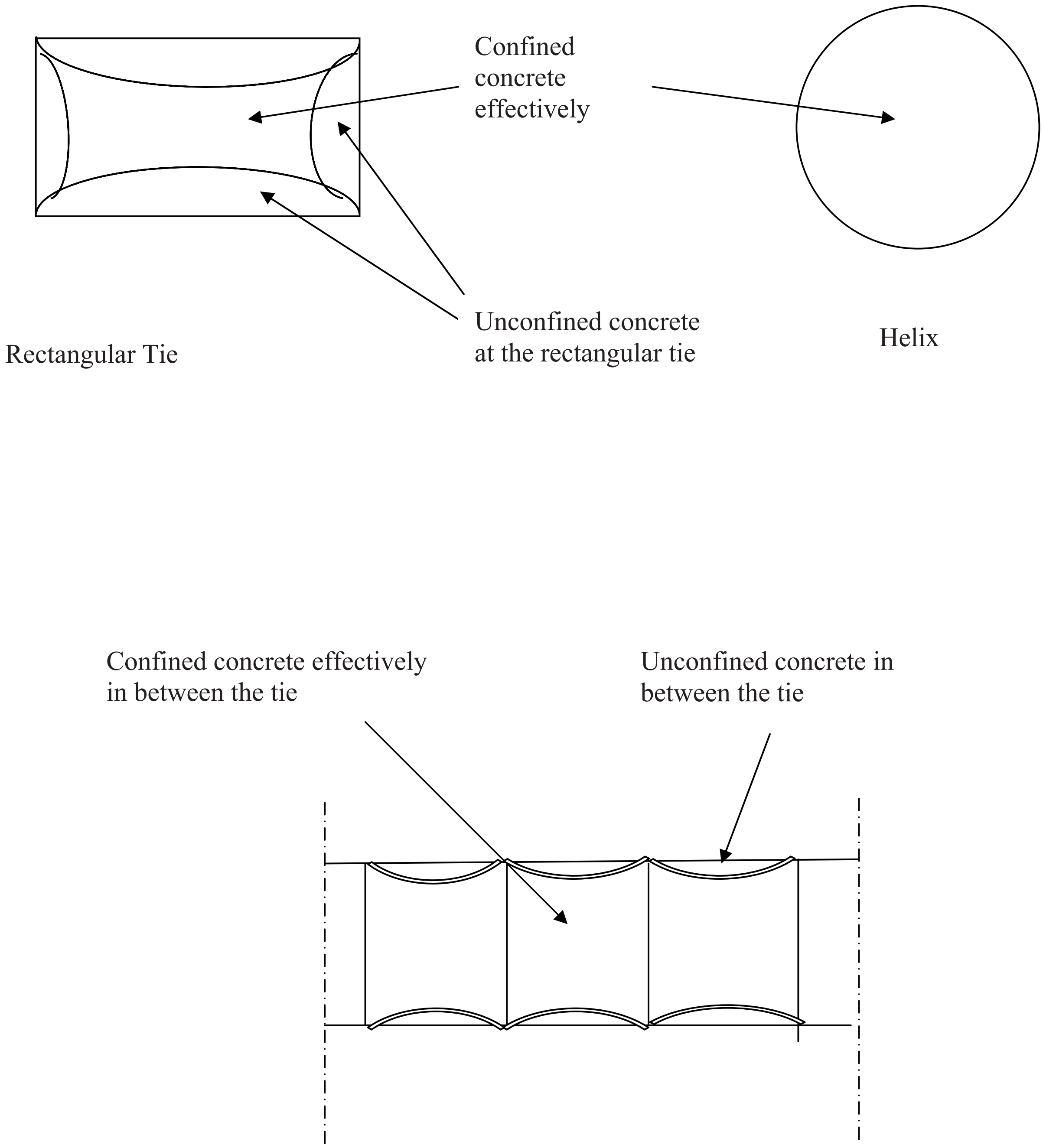
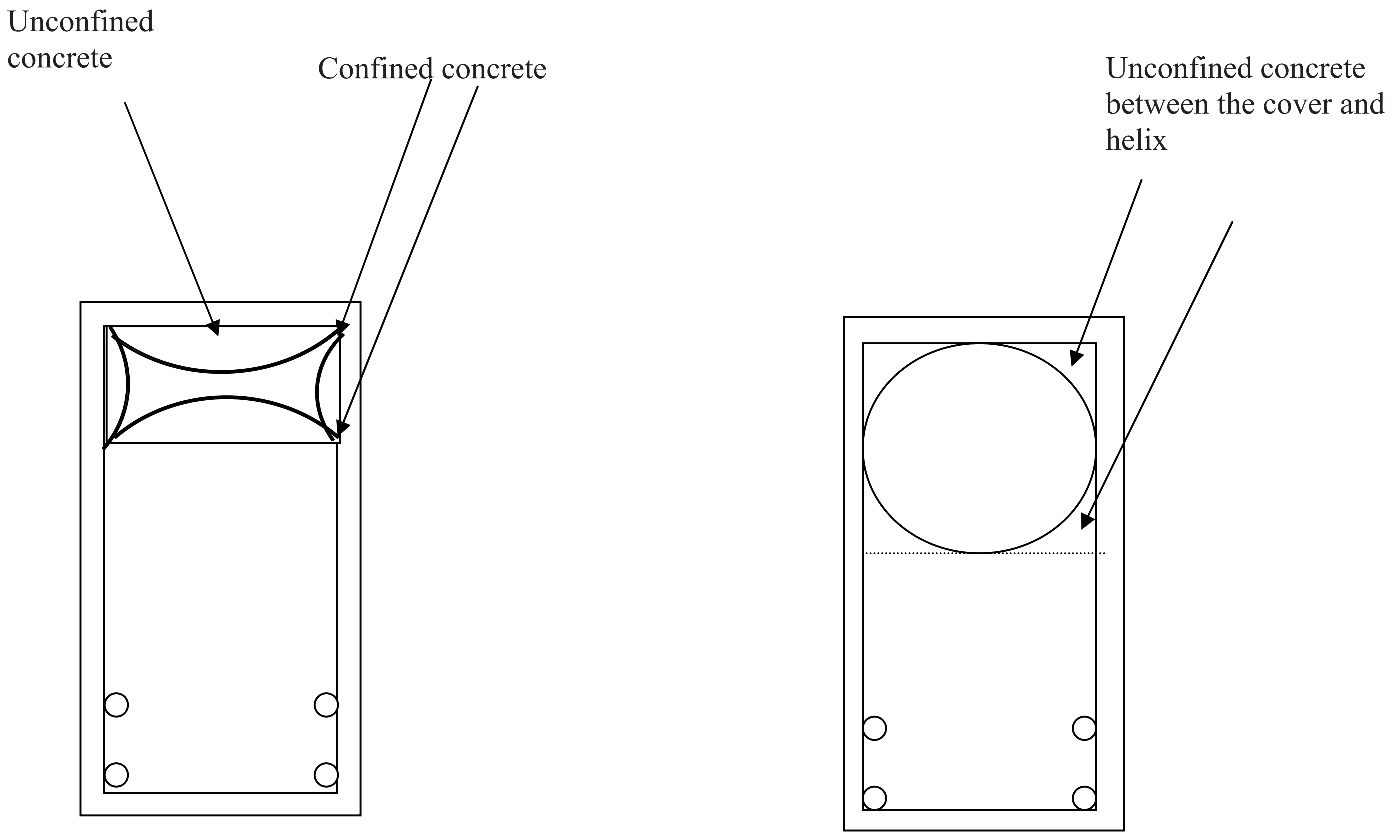


Figure 19. Effective confined concrete for helix and rectangular tie



Beam confined using
rectangular tie.

Beam helically confined

Figure 20. Confined and unconfined compression concrete in beams